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New approaches in harnessing wave energy: With special attention to small islands

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ABSTRACT

The application of renewable energies has increased rapidly in the previous decade to solve some problems such as growing energy demand and environmental issues. Wave power as a high potential renewable energy, is more predictable compared to other renewable sources. Although there are many research works about wave energy, however a few of them considered a suitable wave energy converter (WEC) as a power system for remote islands. Wave energy potential for remote islands is discussed in this review by regarding environmental impacts, various types of wave energy converters and applied wave power projects for various islands. The results show that wave energy plays a key role for sustainable development of offshore islands by considering the traditional looks and environmental protection.

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Abbreviations: RE, renewable energy; WEC, wave energy converter

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1. Introduction

The usage of renewable energy is defined as a proper solution for generating electricity over the past few years to help solving some problems especially global warming [1]. Many renewable resources like solar, wind, and ocean energy (tide and wave) are assumed as a proper alternatives for traditional energy sources [2]. The wave power resources in the world are estimated around 2 TW [3]. Thus, whereas wave energy is a predictable and abundant energy source with the ability to make a significant supply contribution to the world's electricity demands, this energy is considered to be one of the potential alternative sources [4].

Wave energy is a type of renewable (RE) energy with high power density, high utilization factor [5] and low environmental impact compared to other renewable sources [6]. The wave power of the sea surface is about five times larger than wind power at the level 19.5 m above the sea surface [2]. Generating electricity from waves is predicted to be a new source of renewable energy conversion that become important [7] and is considered in many countries as a major and promising renewable resource [8].

There is a wide variety of wave energy technologies which is related on many factors such as water depth and location (shoreline, near-shore, offshore) [8]. First wave energy converter was patented in 1799 [9]. Since then, although hundreds of devices for extracting the wave energy have been designed and tested, but most of these technologies still need to be improved [10]. Therefore, there has not been a feasible wave energy converter that is introduced for future wave plant [11].

On the other hand, most of remote areas like islands are far from power grid. Therefore, providing electricity in these areas is often costly and non-environmentally friendly. In such cases, applying a renewable energy system in remote places has been the best choice [1]. In some potential islands, the near-shore wave energy is examined to be a proper renewable energy sources for power supply [12].

Although there are many research articles about wave power energy [2,5,8,13–15], but a few of them have considered a suitable wave energy converter (WEC) as a power system for remote islands [10,12]. The objective of present paper is to review the recent works about extraction of electricity from wave energy and to evaluate the new applied converters for electrification of small islands.

2. Wave energy

Using wave energy as a potential source of RE, offers significant advantages as follows:

1. Wave energy has the highest energy density among all the renewable energy sources [16,17].
2. There is a low level of negative environmental impact for wave energy. Offshore wave devices have the lowest impact [18].
3. The natural seasonal changes of wave power are compatible with the electricity demand changes [18–20].
4. Wave energy is predictable [21].
5. Power extraction from wave energy is continuous in a day (about 90 percent of the time compare to 20 to 30 percent for wind and solar) [18].

Therefore, wave energy appears to be one of the promising energy sources among the renewable energies [4,22].

3. Wave power potential

According to the International Energy Agency (IEA), the global oceans contain the capacity of 93,100 TWh of power per year [15]. Approximately, the capacity for the wave energy is reported to be 8000 to 80,000 TWh/year in the entire oceans [23].

The feasibility study for wave energy is started by wave data collection. Using available atlas, atmospheric data from data resources or buoy data as a measurement device [24]. After data collection, a model for wave power estimation is presented.

Sea waves are composition of many waves with different frequencies, amplitudes and directions. Therefore, wave power level is defined as [2]:

$$P = \rho g \int_0^{2\pi} \int_0^{\infty} Cg(f,h)\, S(f,\theta) df\, d\theta \tag{1}$$

where, $s(f,\theta)$ is wave spectrum with unit m^2/Hz and describes how different wave frequencies and angles, (f,θ), effect wave power level. P is the wave power, ρ is the mass density of water (1025 kg/m^3), g is the gravitational acceleration, h is the water depth and Cg is the group velocity that is defined as:

$$Cg(f,h) = \frac{g}{4\pi f}\left(1 + \frac{2kh}{\sin\, h(2kh)}\right) \tan\, h(kh) \tag{2}$$

where, $k = 2\pi/L$ is the wave number and L is the wavelength.

For deep water, $Cg = g/4\pi f$, thus:

$$P = \frac{\rho g^2}{4\pi} \int_0^{2\pi} \int_0^{\infty} f^{-1} S(f,\theta) df\, d\theta \tag{3}$$

And the spectral moments (m) of order n is defined as [11]:

$$m_n = \int_0^{2\pi} \int_0^{\infty} f^n S(f,\theta) df\, d\theta \tag{4}$$

For simplicity, wave is assumed in a certain direction. Spectral moment is considered in two orders in term of the energy period (T_e) and the significant wave height (H_s):

$$T_e = T_{-1,0} = \frac{m_{-1}}{m_0} \tag{5}$$

$$H_s = H_{m0} = 4(m_0)^{1/2} \tag{6}$$

Hence, the wave energy power is approximately calculated by:

$$P = \frac{\rho g^2}{64\pi} T_e H_s^2 \cong 0.5 T_e H_s^2 \frac{kW}{m} \tag{7}$$

4. Wave power environmental impact

Nowadays, the greenhouse gases in the world are increased due to traditional methods of energy production. Fifty percent greenhouse emission reduction is set until 2050 by the Kyoto protocol. For this purpose, RE sources have had an essential role on CO_2 emissions reduction [25]. Renewable technologies are considered as clean sources of energy, which could minimize environmental impacts. RE technologies provide an excellent opportunity for mitigation of greenhouse gas emission and reducing global warming [26]. In this section, the environmental impact of wave energy, both positive and negative is considered.

The first essential influence of wave energy as a renewable energy is introduced as reduction of pollutant emissions, which have been raised by fuel combustion. The Fig. 1 demonstrates the world CO_2 emission from fuel combustion [1]. Among the renewable energy sources, wave energy is seen as an enormous source of renewable energy with limited negative environmental impacts [2].

CO_2 emissions from fuel combustion are produced from coal, oil and gas [27]. It has estimated that 300 kg of CO_2 could be avoided for each MWh generated by ocean energy [28]. Vicinaza et al. [29] concluded that wave energy plant for Sardinia Island is an environmentally sustainable solution due to minimum impact on environment.

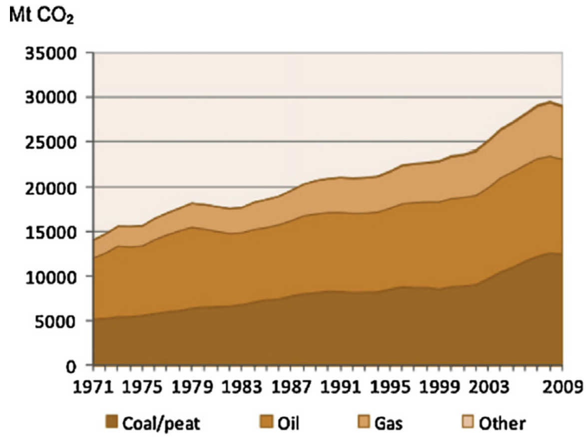

Fig.1. World CO_2 emissions from fuel combustion.

The second benefit of applying wave energy is a tourism impact. The most important matters related to planning for sustainable development of offshore islands are the number of tourists and keeping high-quality environment. Thus, it is necessary to maintain a natural ecosystem environment including existing features of historical culture and suitable tourism policies. Therefore establishment of renewable energy systems for islands would greatly have positive effects on the tourism industry [30].

The last advantage for application of RE for remote locations and islands has been modern development. For example improving the green buildings to make building-integrated photovoltaic (BIPV) design and construction could create the modern-looking buildings [30].

Although wave energy has many advantages, a few disadvantages such as whale killing may be applied by using this energy [5]. Furthermore, some wave converters such as Oyster have produced noise pollution and disturbing wildlife. However, most of this noise is expected to be masked by the wind and waves [31]. Construction and operation of large wind farms will disturb the people or wildlife of coastline areas [32]. Authors in [6] discussed about a few other negative impact of wave farm such as changing the fish population by larvae transportation.

Cle´ment et al. [33] summarized the environmental impact of wave energy conversion technologies as shown in Table 1 [33].

Table 1
Some environmental effects of WECs.

Type of environmental effect	Rate of effect
Land use	Weak
Construction and maintenance	Weak
Coastal erosion	Weak–medium
Fish and Marine biota	Weak
Noise	Weak

5. Wave Energy Converters (WECs)

Extraction of wave energy has been one the most challenging issue for designing a renewable power plant in the last decade [10,34]. Technologies for harnessing wave energy are still in the developing stage. Each technology has different efficiency for various locations [2]. Therefore, choosing a proper WEC for each situation is important.

Generating large amounts of electricity from wave energy has been known since the 1970s when the first wave energy devices were deployed [35]. Currently there are about 200 different wave energy devices in various stages of development and testing [35]. The first practical unit of wave energy was constructed in 1910 by using an oscillating water column system [4]. However the most effective converters by regarding output power was introduced and applied in recent years. Thus, the new wave converters by considering applied projects will be discussed and compared in this paper.

Nowadays new concepts of WECs have introduced and recent technologies have replaced with old ones [8]. Majority of wave energy conversions techniques have been patented in Japan, North America, and Europe [18]. There are wide varieties of WECs and different classifications [11,36–39]. The Environmental Impact Assessment (EIA) proposed a new classifications for wave energy converters based on their parameters such as distance (D), stabilizing (S), vertical obstruction (z/d), horizontal obstruction (w/a) and power (P). On the other side there is the traditional classes of wave energy as shown in Fig. 2 [8,32,40].

As illustrated in chart of Fig. 3, the green circles show a few samples of available wave energy converters.

In this paper wave converters are categorized in three group base on applied location. Some devices can be located on the shoreline, near shore and offshore [41].

5.1. Shoreline WECs

Shoreline energy converters are located entirely on shore [42]. Shoreline devices have the advantages of easier installation and maintenance. Furthermore, these devices do not require deep-water moorings and long underwater electrical cables [8]. These types of WECs are close to the national electricity grid [41]. However, low wave power in shallow water is one of the essential disadvantages for shore mounted devices [18]. Some examples for this type of WECs are provided as below:

5.1.1. SDE Sea Wave

SDE Sea Wave is one of the new onshore converters that produce proper range of power. The construction of 250 kWh is begun in 2010. As shown in Fig. 3, SDE works based on Buoy method. The buoys are placed on a breakwater and they move up and down based on the frequency of sea waves. Buoys push a hydraulic liquid for conversion of energy to circular system. Finally the generator will be operated. There is a plan to construct a 100 MWh power plants in the islands of Zanzibar and Kosrae, Micronesia by using this converter [43].

5.1.2. Oscillating water column

Although this method of wave capture is not a new approach, however it has been improved in recent years to produce more power. Islay LIMPET is one of converters that has been working base on this method [44]. In these systems, waves are trapped in a reservoir and the rise and fall of the water moves a column of air to drives a turbine [41]. A low-pressure wells turbine is often used in this application. It has presented that one of the advantages of the OWC concept is the simplicity[18]. Fig. 4 shows the illustration of OWC [36].

This system has a maximum output of 500 KW. It is ideal for locations where there is strong wave energy, such as breakwaters, coastal defenses, land reclamation schemes and harbor walls. This form of energy generation is suitable for producing power for small islands with high level of wave energy [8]. Yaakob et al. [45] from marine laboratory of University Technology Malaysia developed an OWC device and recommended this converter for the climate condition with low wave height such as Malaysia. Antonio F. et al. [46] studied the equipments of OWC converter for a

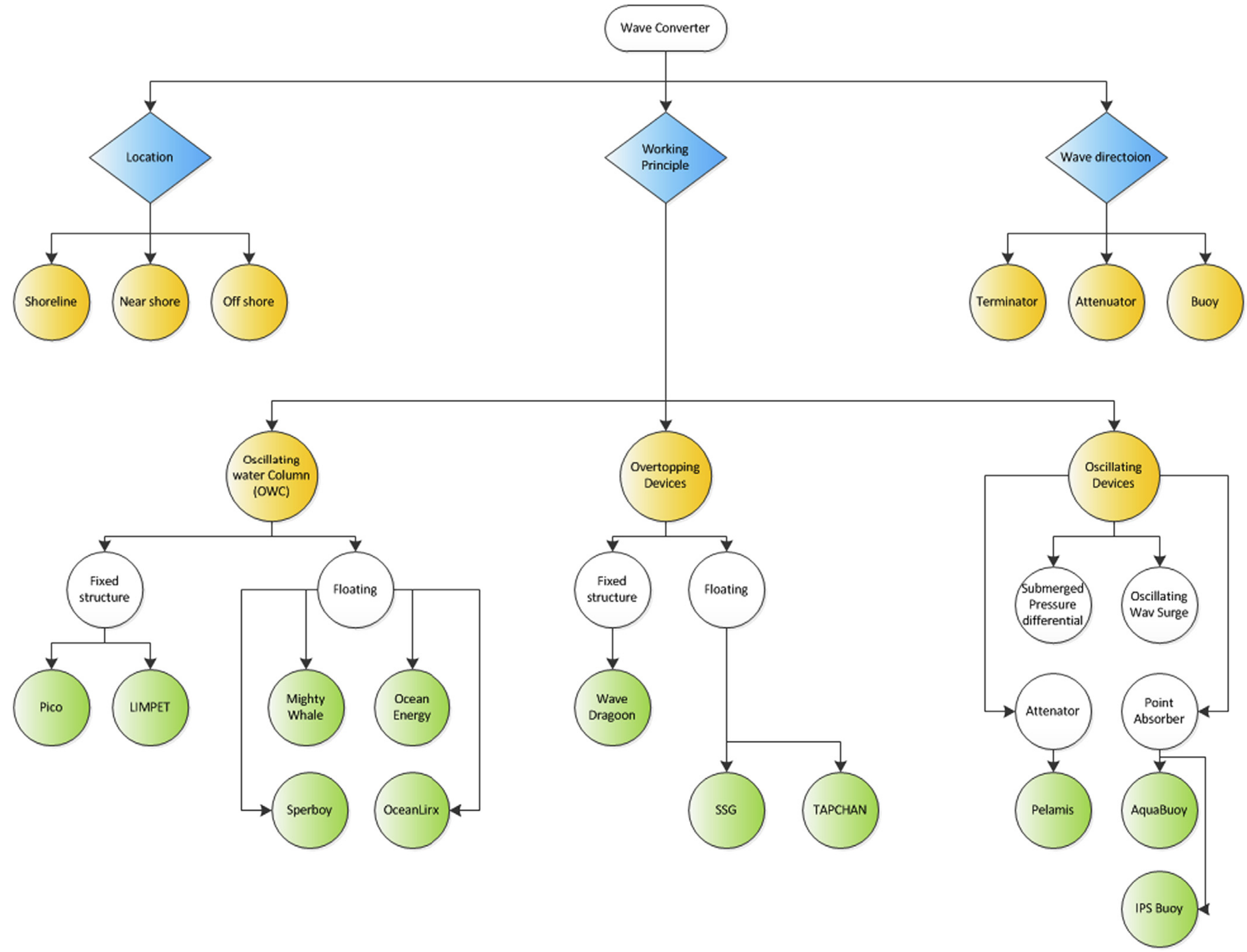

Fig. 2. Wave Converter classification.

shoreline wave plant in Pico Island, Azores. Josset in [47] presented a time domain simulation model for a wave plant by OWC.

5.1.3. *Other innovative devices:*

Zhang et al. [48] discussed about a wave plant by using 5 kW Power Take Off (PTO) converter in Aoshanwei Island, Shandong province, China. Schematic design of this hydraulic device is shown in Fig. 5.

Another researcher et al. [49] developed a Sea Slot-cone Generator (SSG) converter which is classified in the category of overtopping converters. This device is installed as a pilot project in shoreline of Norway. SSG has used four Kaplan turbines that are designed in reservoirs as shown in Fig. 6 [49].

There have been some other efforts among the researchers to develop the performance of available OWCs by novelty on air turbines [50].

5.2. *Nearshore WECs*

Near shore devices capture wave energy in the nearshore and convert it into electricity in an onshore facility. These devices are often attached to the seabed, which provides a suitable situation for oscillating body to work [51]. According to comparison that is demonstrated in Table 2, Oyster and AWS are two powerful converters that build in 2005 and 2003.

Fig. 3. SDE Sea Wave Converter.

5.2.1. *Oyster*

Oyster wave power technology captures energy in nearshore waves and converts it into clean electricity [31]. Oyster is a wave-powered pump which pushes high pressure water to drive an onshore hydro-electric turbine [8]. The size and operation of Oyster converter is shown in Fig. 7 [52] and Fig. 8 [53].

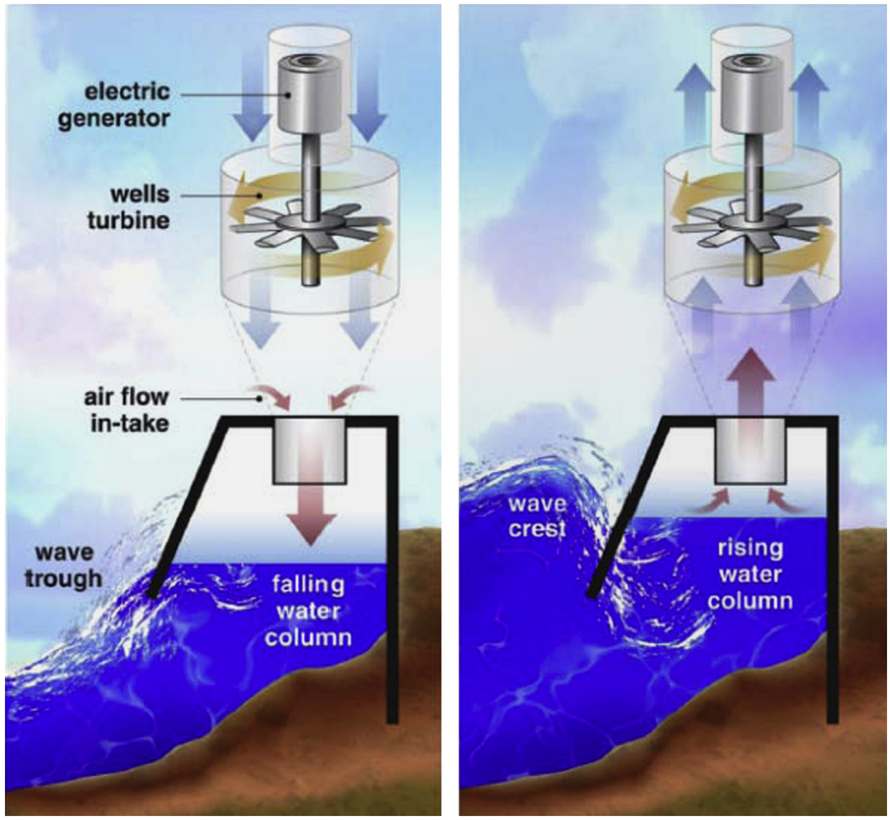

Fig. 4. Illustration of an Oscillating Water Column.

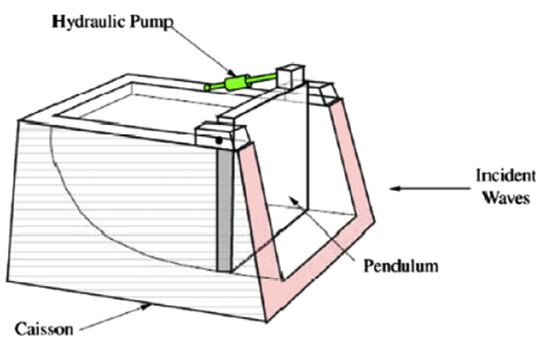

Fig. 5. Schematic design of PTO converter.

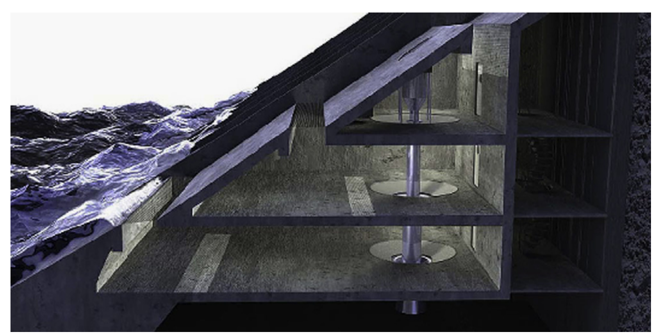

Fig. 6. SSG converter designed and installed in Norway.

A farm of 20 Oyster units could produces enough energy to power 9000 homes [31].

5.2.2. The Archimedes Wave Swing (AWS)

Point absorber is defined as a latest technology for wave extraction and works based on a floating body with a linear generator [37]. There are many types of point absorber devices that are investigated in previous works [40]. AWS as a point absorber converter uses the pressure difference above the device between wave crests and troughs. AWS consist of a sea bed fixed air-filled cylindrical chamber and a moveable cylinder. When a crest passes over the converter, the upper cylinder will go down due to water pressures and air within the cylinder. As a trough passes over, the water pressure on the device will be reduced and the upper cylinder rises [18].

As an advantage of this device, it is fully submerged and there is not slamming forces experienced by floating devices as shown in Fig. 9 [54,55].

Table 2
Comparison between some near shore WECs.

Device	Year build	Power rating (MW)	Location
SeaRaser	2008	1	Nearshore
Oyster	2005	31.5	Nearshore
AWS	2003	5–6	Nearshore
WaveRoller	1994	1.3 per plate	Nearshore

5.3. Offshore WECs

Whereas deep water sea waves offer large energy fluxes with predictable conditions [29,54], more researchers have focused on offshore converters [56]. Offshore energy converters are deployed in deep waters without an onshore installation (Between 30 m and 100 m) [42,57]. These tools, which sometimes classified as third generation devices are classified under oscillating bodies. Offshore wave energy converters are in general more complex due to

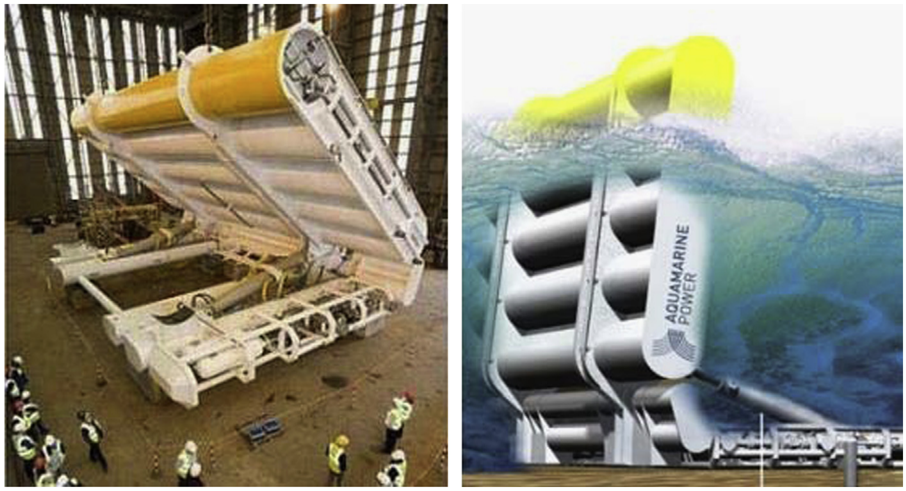

Fig. 7. Size and operation of Oyster converter.

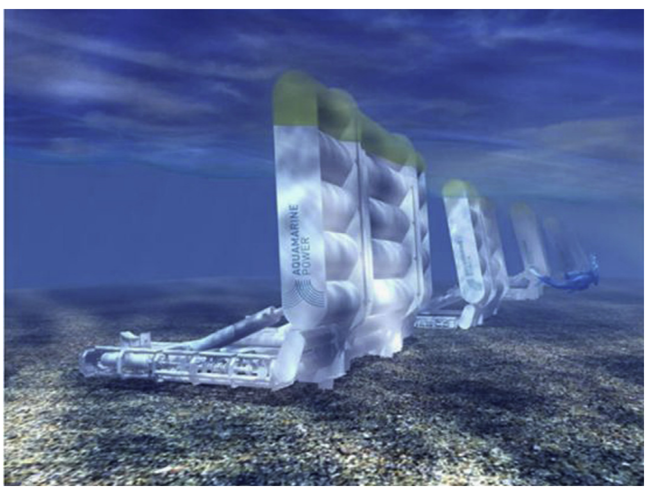

Fig. 8. Oyster devices while working underwater.

Fig. 9. Archimedes Wave Swing, AWS.

problem associated with mooring point, maintenance and underwater electrical cables. However in recent years some effective offshore systems have built [8]. A comparison table provided as below (Table 3).

Although some other converters like Anaconda and FlanSea have built in recent years, however most used and applied devices for large amount of power are listed in above table. Wave Dragoon and AWS-iii are two wave converters with high power.

Table 3
Comparison between some offshore WECs.

Device	Year build	Power rating (MW)	Location
AWS-iii	2010	2.5	Offshore
Aqua Buoy	2003	1	Offshore
Wave Dragon	2003	11	Offshore
Wave Star	2000	0.6	Offshore
Pelamis	1998	0.75	Offshore

5.3.1. *AWS-III*

The AWS-III technology consists of a multi-cell array of flexible absorbers, which convert wave power to pneumatic power through compression of air within cells that are inter-connected. Turbine-generator sets are provided to convert the pneumatic power to electricity [58] as shown in Fig. 10 [59].

The AWS-III will be slack moored in water depths of around 100 m using standard mooring spreads. Each AWS-III will be connected to a central offshore substation via a high-voltage central link [58].

5.3.2. *Wave Dragoon*

The Wave Dragon is an offshore floating device uses a pair of curved wave reflectors to force ocean waves for flowing over a ramp and into a reservoir. The water is let out through a number of turbines. Wave Dragon is designed to overtopping water into the reservoir for high power production [41] as shown in Figs. 11 and 12 [60].

The main body or platform consists of one large floating reservoir. The wave dragon is large and heavy to reduce rolling and keep the platform stable. The total steel weight of the main body plus the ramp is 150 tons, thus 87 tons of water must be added to achieve the 237 tons total weight for stable operation [8]. Wave Dragon has applied for deploying a 7 MW wave plant in the coast of Wales, UK in 2011 [61]. Fadaeenejad et al. [62] suggested wave dragoon for offshore location in Mazandaran, Iran (south coast of Caspian Sea). Fig. 12 shows a wave dragon converter [63].

Both Wave Dragoon and AWS-iii have been working base on Surface-following attenuator capture method.

Fig. 10. Applied model of AWS-III in Loch Ness.

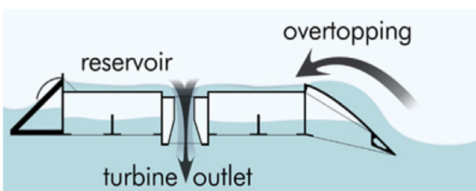

Fig. 11. Operating diagram of wave dragoon.

Fig. 12. Applied wave dragoon converter.

5.3.3. Pelamis

Among the all WECs, Pelamis is considered as a most applied converter in various locations. Deane et al. [64] presented an economic analysis of 500 MW wave power plant for Ireland by using Pelamis. Shetland and Bernera Islands in Scotland applied Pelamis to make their wave power plant in recent years. Fig. 13 demonstrates the Pelamis buoyed for Shetland Islands in 2011 [65,66].

Although there are many WECs, however researchers believe that available wave energy converters have not been cost effective and technology of WEC must be developing in future [67].

Finding a suitable wave energy converter depends on various factors such as wave height, period of wave, depth of water and geography conditions [68]. Therefore, investigation about wave characteristics [69] before doing feasibility study is assumed necessary.

Fig. 13. Pelamis for Islands wave project in Scotland.

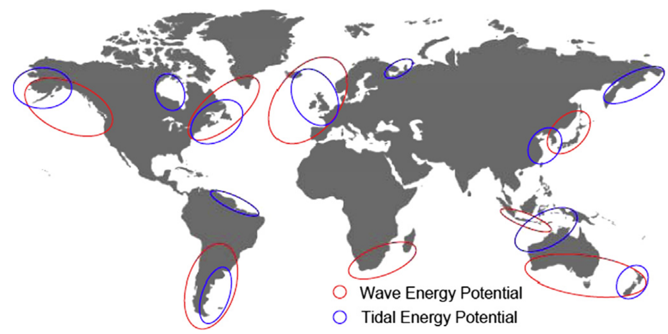

Fig. 14. World wave energy potential.

6. Wave power for remote Islands

Whereas grid extension for remote areas is not reasonable by considering installation cost, the usage of diesel generators have been a simple option for remote area electrification [70]. Therefore, the most small islands and remote communities around the world need the imported fossil fuels for their energy requirements. These communities are dependent to diesel fuel price, and high operation and maintenance costs including fuel transportation. Therefore, application of renewable stand-alone power system by using available energy source is assumed as a suitable solution for remote locations [1]. Kaldellis in [71] discussed about the necessity of remote islands electrification by a renewable solutions. By regarding availability of hydro potential and wave energy without any pollution [70].

As shown in Fig. 14, in most places with high potential of wave energy there are considered in near islands, especially in Southeast Asia [41,72].

On the other side, some researchers in recent years investigated the application of wave energy as an electricity source for island. Table 4 shows many articles for application of wave power plant for the Islands in recent years.

The data collection about wave height, wave period and other characteristics of wave energy in islands is done by environmental and geographical researchers. Arinaga et al. [73] provided a global atlas of wave energy that is useful for future researchers. B. Aydogan presented a wave data atlas for Black sea [74]. These types of atlases are effective for further investigation of wave potential in the Islands. Stephenson measured the wave height, period and direction in various situations on Kaikura peninsula, south island, New Zealand [75]. Another author did a same research for Island, Maldiv [68]. Brander et al. [76] presented the wave characteristics across a reef platform. His study can be used by engineering researchers for Warraber Island. Moreover, wave characteristics of this Island in Australia is studied in [77].

Table 4
Applied research works for wave energy in Islands.

Year	Author	Island	Suggested Converter
2013	Berna Ayat	Greek Islands	Pelamis, Wave dragon, Aqua buoy
2013	D. Vicinanza	Sardinia island, Italy	Pelamis, CETO, OTEC
2012	Eugen Rusu	Madeira Islands	Aquabuoy, Wave dragon, Pelamis
2012	Jean Philippe Praene	reunion Island	–
2012	Liliana Rusu	Azores islands	SEAREV, Floating system
2012	D Zhang	aoshan wei island, shandong province	Pelamis
2012	J.P. Deane	Ireland	Hydrolic PTO
2011	Justin E. Stopa	Hawaiian Islands	–
2010	Scott J. Beatty	Alaskan island	Pelamis
2010	G. Iglesias	La Palma, Spain	–
2009	David Dunnett	Vancouver Island	–
2006	A. Babarit	Yeu island, France	–

As mentioned in Table 4, some of researchers examined the wave potential in various islands. Liu et al. [30] assessed the feasibility study of renewable energy resources such as solar, wind and tidal for Kinmen island. Praene in [78] presented the current status and major achievements of policies and the future objectives in the deployment of renewable energy programs in Reunion island. The author suggested some wave experimental projects for future of this island. Finally, Dunnett [79] evaluated wave energy converters for electricity generation in coastline and islands of Canada. Beatty [80] assessed the technical feasibility of a WEC connection to the island of St. George in Alaska to supply part of electricity demand. Rusu et al. [81] discussed about the wave energy around the Maderia Island by using AVISIO and buoy device. The authors first investigated the wave characteristics and then calculated the wave power. Babarit et al. [82] proposed a 10 MW wave farm in Yeu Island, France. The author compared his suggestion with 10 MW wind farm and concluded that the level of delivered energy for both recommendations is same.

Rusu in [10] did an assessment about wave energy in Archipelago of Azores. Author investigated about some factors such as wave height, wave period, wind rose (directional distribution), frequency of wave in different height and scatter diagram. The wave height average for winter in the case studies in this research is defined around 3.8 m and for total year 2.7 m. Ayat et al. [67] determined the wave energy potential in Greek Islands by using hourly wave data, wave climate simulation within 15 years and scatter diagram. Iglesias provided the feasibility study of wave power in La Palma (northwestern of Canary Islands) in Spain. According to the atmospheric data and wave model, the authors concluded that there are various wave energy potential around the Island and northwest has the highest one [83]. Estopa in [20] considered the potential of wave energy in Hawaiian Islands. In [29] seven sites in Sardinia island of Italy is determined for wave energy potential to help the environment of island.

7. Conclusion

It is concluded that wave energy with a huge power potential and technologies for harnessing wave energy are still in the developing steps. Hence, the results are categorized as below:

- Wave as a predictable source of energy has a high potential of power production base on high power density and high utilization factor.
- Wave potential plays a key role for sustainable development of offshore islands. The wave plant can help such islands by considering environmental aspect, tourist attraction, supplying electricity demand and modernization.
- Choosing a suitable converter depends to the various factors like wave power, depth of water, location etc.
- Researchers in recent years focused on offshore type converters due to large energy flux for waves in deep waters compare to nearshore and shoreline types.
- Among the offshore wave energy converters, Wave Dragoon have the most power rating and Pelamis is defined as the most applied one.

Although there have been a few works for application of wave energy in islands, however the potential for installation of wave power plant in a small remote islands is highlighted in this review. Thus, the proper potential outlook for future development of wave energy in small islands is predicted.

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